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# THE EXCESS FLUX IN THE COSMIC SUBMILLIMETER BACKGROUND RADIATION AND THE PRIMORDIAL DEUTERIUM ABUNDANCE

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## Abstract

Recent measurements (Hayakawa et al. 1987; Matsumoto et al. 1988) of the cosmic background radiation (CBR) show an enhanced flux in the submillimeter (Wien) regime, compared to the spectrum of a 2.7 K blackbody. Thermal Comptonization of the relic radiation by a hot nonrelativistic plasma has long been known (Zeldovich and Sunyaev 1969) to produce distortions in the CBR spectrum, similar to what has now been observed. Heating of the primeval plasma to temperatures  $T \sim 10^6 - 10^8$  K could result from the injection of subcosmic ray protons at epoch  $z \sim 10-100$ . The intensity of the subcosmic ray flux that provides conditions needed to explain the submillimeter excess by thermal Comptonization also leads to the production of cosmologically significant amounts of deuterium in collisions between subcosmic ray protons and primordial protons and  $\alpha$ -particles. However, the amount of lithium produced through  $\alpha$ - $\alpha$  reactions is in conflict with the observed  ${}^7\text{Li}$  abundance (Epstein 1977). If lithium is depleted, for example, by processing through Population II stars, arguments for the baryon content of the universe based on primordial deuterium and  ${}^3\text{He}$  abundances are weakened.

Distortions in the spectrum of the CBR give information on the conditions of the early universe following recombination of the primeval plasma at  $z \approx 1500$ , and may result from scattering of light by dust (Wright 1981), the existence of a separate class of luminous sources, or from thermal Comptonization of the relic radiation by a hot diffuse plasma. The latter process, known as the Zeldovich-Sunyaev effect, causes a diminution in the intensity of the blackbody radiation in the Rayleigh-Jeans regime and an enhancement in the Wien regime. Recent observations of an enhancement in the submillimeter regime of the CBR spectrum at  $\lambda > 300 \mu\text{m}$  are compatible with spectral distortions of a 2.7-2.8 K blackbody radiation spectrum by a hot thermal electron plasma with  $y$ -parameter  $\approx 0.02-0.03$  (Hayakawa et al. 1987; Matsumoto et al. 1988).

We consider the possibility that the primeval gas was heated by an intense flux of subcosmic ray protons generated prior to the period of galaxy formation ( $z \gg 5$ ). The existence of sub-GeV protons heating the diffuse plasma has also been considered on other grounds (Ginzburg and Ozernoi 1966; Stebbins and Silk 1986). The acceleration of these particles may have taken place as a result of shocks generated in the plasma, by the dissipation of primeval turbulence, or through acceleration mechanisms associated with hypothetical massive objects such as Population III stars or primordial black holes.

Subcosmic ray protons transfer energy to the background thermal plasma through Coulomb coupling and collective processes, such as Alfvén wave scattering. Here we consider only Coulomb losses. The Coulomb loss rate of a proton with kinetic energy  $E_k = m_p c^2(\gamma - 1)$  is given by

$$-\frac{d\gamma}{dt} = \frac{3m_e \sigma_T c n_e \ln \Lambda}{2m_p \beta}, \quad (1)$$

where the Coulomb logarithm  $\ln \Lambda \equiv 40 \Lambda_{40}$  and the other symbols have their usual meanings. If the baryonic matter in the universe is primarily in the form of diffuse plasma, the gas density at epoch  $z$  is given by  $n_e(z) = n_c \Omega(1+z)^3$ , where the critical density  $n_c = 3H_0^2/8\pi G m_p =$

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$1.1 \times 10^{-5} h_0^2 \text{ cm}^{-3}$ ,  $\Omega$  is the ratio of the gas density to the critical density at the present epoch, and  $H_0 = h_0 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$  is Hubble's constant. The reciprocal of the timescale for energy loss by cosmic expansion is given by  $t_{\text{exp}}^{-1} = |V^{-1}(dV/dt)| = 3(1+z)^{-1} |dz/dt|$ , where  $|dz/dt| = H_0(1+z)^2 (1+\Omega z)^{1/2}$ .

The time evolution of particle energy, referred to unit comoving volume  $V$ , is described by the relation

$$\frac{dQ}{dt} = \frac{dE}{dt} + p \frac{dV}{dt} \quad (2)$$

The term  $dQ/dt$  refers to energy gains and losses; for protons assumed to be impulsively accelerated to a specified energy  $E_k$ ,  $dQ/dt = -m_p c^2 (d\gamma/dt)$ . The nonthermal proton pressure  $p = n_{\text{scr}} m_p c^2 \beta^2 \gamma / 3$ , where  $n_{\text{scr}}(z; \beta)$  is the density of the subcosmic ray protons with velocity  $\beta c$ . Rewriting equation (2) as an evolution equation in terms of  $z$  gives

$$\frac{d\gamma}{dz} = \frac{\beta^2 \gamma}{1+z} - \frac{2.3 \times 10^{-3} \Lambda_{40} h_0 \Omega (1+z)}{\beta \sqrt{1+\Omega z}} \quad (3)$$

Equation (2) also applies to the time evolution of the plasma temperature. In this case, the heating term  $dQ/dt$  is given by the relation  $dE_{\text{coul}}/dt = m_p c^2 \xi (d\gamma/dt)$ , where  $\xi \equiv n_{\text{scr}}/n_e$  represents the fraction of protons impulsively accelerated. Besides losses due to cosmic expansion, the most important energy losses of the thermal plasma are Compton losses of the electrons on the CMB, which is the source of the distortion of the CMB, and bremsstrahlung emission. The Compton loss rate is given by

$$-\frac{dE_{\text{Comp}}}{dt} = 4 \sigma_T c \theta U_{\text{CBR}} \quad (4)$$

where  $\theta \equiv kT/m_e c^2$ . The CBR energy density  $U_{\text{CBR}} = 4.0 \times 10^{-13} (1+z)^4 \text{ erg cm}^{-3}$  for a present CBR temperature of 2.7 K. Relativistic corrections to equation (4) are unimportant since  $\theta \ll 1$ .

The nonrelativistic bremsstrahlung energy loss rate is given with factor-of-2 accuracy in the Born regime ( $T \gg 10^5 \text{ K}$ ) by the expression

$$-\frac{dE_{\text{ff}}}{dt} \equiv \left(\frac{2}{\pi}\right)^{3/2} \alpha_f \sigma_T c (m_e c^2) n_e(z) \theta^{1/2} \ln 4 \quad (5)$$

Bremsstrahlung losses to particles heavier than hydrogen represent a small correction and are neglected.

Since the pressure of the diffuse primordial plasma is accurately described by the ideal gas law,  $dE/dt = (3/2)m_e c^2 d\theta/dt$  in equation (2). Rewriting this equation for  $\theta$  as a function of  $z$  gives

$$\frac{d\theta}{dz} = \frac{2\theta}{1+z} - \left|\frac{dt}{dz}\right| c \sigma_T \left[ \frac{\ln \Lambda n_{\text{scr}}(z; \beta)}{\beta} - \frac{8\theta}{3} \frac{U_{\text{CBR}}}{m_e c^2} - \frac{2}{3} \left(\frac{2}{\pi}\right)^{3/2} \alpha_f n_e(z) \theta^{1/2} \ln 4 \right] \quad (6)$$

for the time evolution of the electron temperature.

For simplicity, we solve equations (3) and (6) following the impulsive injection of monoenergetic protons at epoch  $z_i$ . Permitted values of  $\xi$ ,  $E_k$ , and  $z_i$  are constrained by the requirement that the  $y$ -parameter, given through the relation

$$y = \sigma_T c \int dz \left|\frac{dt}{dz}\right| \theta(z) n_e(z) \equiv 0.07 h_0 \Omega \int dz \frac{\theta(z) (1+z)}{\sqrt{1+\Omega z}} \quad (7)$$

be in the range 0.02-0.03 (Hayakawa et al. 1987; Matsumoto et al. 1988).

Breakup reactions in collisions between subcosmic ray protons and  $\alpha$ -particles in the diffuse plasma provide a source of deuterium,  $^3\text{He}$  and  $^3\text{H}$  (which decays promptly on cosmic

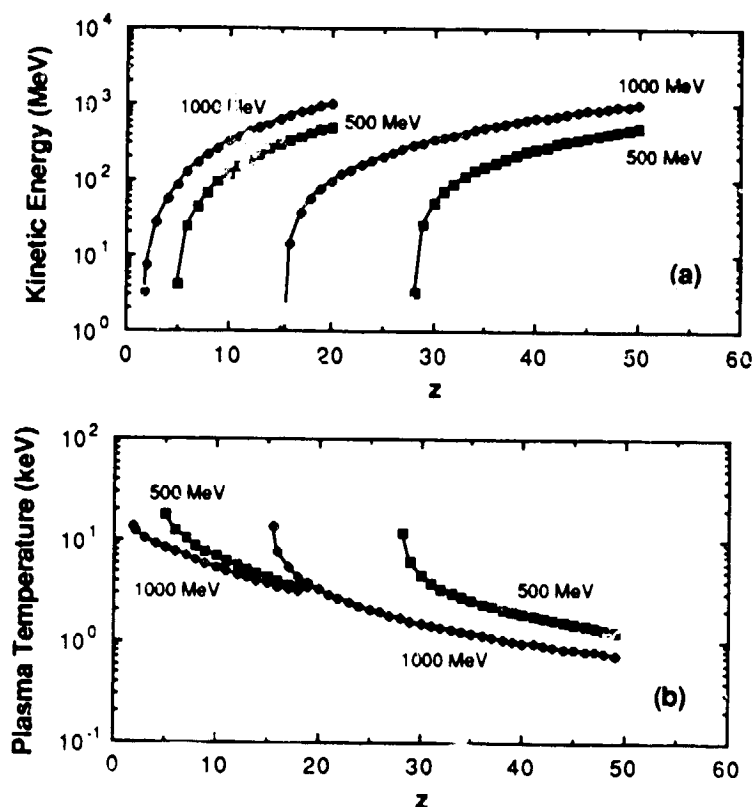
times to  ${}^3\text{He}$ ). The deuterium enrichment factor for  $p$ - $\alpha$  reactions is given by

$$\eta_d \equiv \int dt \frac{1}{n_p} \frac{dn_d}{dt} = c \int dz \beta(z) \sigma_d(\beta) \frac{n_\alpha(z)}{n_p(z)} n_{scr}(z; \beta) \left| \frac{dt}{dz} \right|, \quad (8)$$

where  $\sigma_d$  is the  $p+\alpha \rightarrow$  deuterium cross section (Meyer 1972; Reeves 1974). Deuterium production through the reaction  $p+p \rightarrow \pi^+ +$  deuterium when  $E_k \geq 300$  MeV is also included. The intensity of subcosmic ray protons with energies above the pion-production threshold is, however, constrained by the diffuse extragalactic X- and  $\gamma$ -ray background radiation, since neutral-pion decay  $\gamma$ -ray production in the reaction  $p + p \rightarrow \pi^0 \rightarrow 2\gamma$  cannot overproduce the measured diffuse background flux (Epstein 1977). To estimate the importance of this process, we use an equation similar to (8) to calculate the neutral pion "enrichment" factor  $\eta_{\pi^0}$ , representing the number of neutral pions produced per proton, and use an evolution equation to calculate the the presently observed spectral flux.

Results are shown in Fig. 1 and listed in Table I, which gives values of  $\xi$  required to produce a hot plasma with  $y$ -parameter between 0.02 and 0.03. Here we consider the possibility of a universe with  $\Omega=1$  in baryonic matter. We let  $h_0 = 0.5$ , and treat injection energies  $E_k = 500$  MeV and 1 GeV. After injection, protons initially lose energy primarily through cosmic expansion, but Coulomb losses tend to dominate when  $E_k \leq 100$  MeV. As can be seen from Fig. 1b, the background plasma is heated to  $T \sim 1$ -10 keV. In order to secure agreement with the submillimeter excess, values of  $\xi \sim 10^{-3}$  are required. Thus only  $\sim 0.1\%$  of the primeval protons have to be processed through an energetic phase in order to provide the necessary heating of the primeval plasma.

Fig. 1. Dependence of proton kinetic energy (Fig. 1a) and plasma temperature (Fig. 1b) on epoch  $z$ , with  $h_0=0.5$  and  $\Omega=1$  in baryonic matter. Labels refer to the initial kinetic energy of the subcosmic ray protons, injected instantaneously at  $z=20$  and  $z=50$ . The injection parameters are bracketed by the values given in Table I, and correspond to  $y \approx 0.022$ . The sharp increase in plasma temperature as the proton energy becomes less than  $\sim 100$  MeV is a result of the monoenergetic, impulsive injection conditions assumed in the calculation.



The intensity of the presently observed spectral flux resulting from  $\pi^0$ -decay gamma radiation depends sensitively on the injection energy of the subcosmic ray protons. When  $E_k \leq 600$  MeV, it is easy to obtain agreement with the  $\gamma$ -ray background, whereas  $\gamma$  rays are overproduced when  $E_k \geq 1$  GeV. One can also show that the redshifted bremsstrahlung radiation from the hot diffuse plasma does not conflict with the ultraviolet background, since the energy density in this radiation represents at most  $\sim 0.5\%$  of the energy density in the CBR.

We find that the deuterium enrichment following subcosmic ray interactions in the early universe is in the range  $\eta_d \sim 0.5$ - $5 \times 10^{-5}$ . Values of the deuterium abundance ratio in the solar

system and interstellar medium are  $1.4 \times 10^{-5}$  and  $1.5-3 \times 10^{-5}$ , respectively (Boesgaard and Steigman 1985). Characterization of the pregalactic value of  $\eta_d$  depends on models for processing deuterium and  $^3\text{He}$  in stars, and could range anywhere between  $10^{-5}$  and  $10^{-4}$  (Yang et al. 1984). Thus we see that this model could produce all of the deuterium and  $^3\text{He}$  presently observed, and makes the specific prediction that  $^3\text{He}$  is originally produced in roughly equal amounts as deuterium.

TABLE I  
Deuterium,  $^3\text{He}$ , and Neutral Pion Enrichment Factors Resulting from Subcosmic Ray Heating of the Primeval Plasma by the Injection of Subcosmic Rays with Energy  $E_k$  at Epoch  $z_i$

$z_i$	$E_k(\text{MeV})$	$\xi (\times 10^3)^*$	Enrichment Factors ( $\times 10^6$ )		
			$\eta_d$	$\eta^3\text{He}$	$\eta^7\text{Li}$
10.	500.	3.-4.	5.5-7.3	7.5-10.	0.20-0.27
	1000.	4.-5.	14.-17.	16.-20.	0.22-0.28
20.	500.	1.2-1.5	5.4-6.7	7.4-9.2	0.20-0.25
	1000.	1.3-1.6	11.-15.	13.-17.	0.19-0.23
50.	500.	1.1-1.4	13.-16.	18.-22.	0.47-0.59
	1000.	0.75-0.90	22.-26.	25.-31.	0.36-0.43
100.	500.	1.7-2.2	30.-39.	42.-54.	1.0-1.4
	1000.	1.0-1.3	57.-72.	66.-83.	0.9-1.2

\*  $\xi$  is the fraction of protons in the primeval gas processed through a subcosmic ray phase in order to obtain values of the Compton  $y$ -parameter between 0.02 and 0.03.

The lithium production in the present model is, however, in conflict with the observed abundance by several orders of magnitude (Table II). In the case of Population II stars, the  $^7\text{Li}$  abundance  $\eta^7\text{Li} \approx 1.2 \times 10^{-10}$  (Boesgaard and Steigman 1985). This discrepancy could be avoided if lithium were depleted in old stellar populations (Kawano et al. 1988), or if protons are preferentially accelerated compared to  $\alpha$ -particles (Epstein 1977; here we assumed that  $\alpha$ -particles comprise 8%, by number, of the subcosmic rays). In this case, the heating of the universe by subcosmic rays would have serious consequences for the standard model of primordial nucleosynthesis, since arguments based on the observed deuterium abundance have been used to lend strong support to the conclusion that the synthesis of the bulk of the light elements takes place in the big bang.

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